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PIPE REPLACEMENT BY AGE ONLY, HOW MISLEADING COULD IT BE?

M.A. Pardo[a*] and J. Valdes-Abellan[a]

[a] *Department of Civil Engineering, University of Alicante, Alicante, Spain.* mpardo@ua.es

ABSTRACT

Traditional methods for prioritizing the renewal of water are based on heuristic models, such as the number of breaks per length, rule-of-thumb, records held by the water utility companies. Efficient management of water distribution networks involves factoring in water and energy losses as the key criteria for planning pipe renewal. Prioritizing the replacement of a pipe according to the highest value of unit headloss due to ageing does not consider the impact on water and energy consumption for the whole network. Thus, this paper proposes a methodology to prioritize pipe replacement according to water and energy savings per monetary unit invested—economic prioritization—. This renewal plan shows different results if comparing with replacing pipelines with regard to age and it requires calculating water and energy audits of the water distribution networks. Moreover, the required time to recover the investment performed needs to be calculated. The methodology proposed in this work is compared to the unit headloss criterion used in a real water-pressurized network. The results demonstrate that using the unit headloss criterion neither water, energy nor the investment is optimized. Significant water and energy savings are not fully exploited.

KEYWORDS

Economic prioritization, energy efficiency, leakage, pipe replacement, water efficiency

1. INTRODUCTION

The U.S. Environmental Protection Agency declared the nation's drinking water utilities need in infrastructure investments $334.8 Billion (EPA, 2013) over the next 20 years. England and Wales where water companies invested GBP 4.9 billion in 2014-15 (OFWAT, 2018) are also declaring high needs and investments in water pressurized networks. So, pipe replacement has become an important challenge for utility managers, who must ensure safe water quality and structural performance with the minimization of the resources consumed.

Traditionally, decision-making alternatives for the rehabilitation of water distribution networks (WDN) have been based on indices such as the number of breaks per pipe (Hong. et. al., 2006) and the evolution of breakage rate with time (Alvisi and Francini, 2010). Some other approaches consider the unitary headloss related to pipe ageing (Kleiner et. al., 2001), the minimization of the investment calculating the optimal pipe renovation period (Shamir and Howard, 1979), or the minimization of the total cost of pipe replacement cycles to infinity (Kleiner et. al., 2001). As this has been one of the hottest topics in the water industry, several decision support tools to obtain pipe replacement scheduling has been developed based on genetic algorithms (Alvisi and Francini, 2006) or on performance indicators (Pinto et al., 2017). Whithout any doubt, management of water losses (Marques and Monteiro, 2003) have become one of the key goals for decision makers and practitioners due to scheduling pipe replacement in predetermined budget constrains (Alvisi and Francini, 2009).

The objective of this work is neither to find the most appropriate model to simulate water leakage nor to calibrate leakage model parameters, but to propose a methodology to prioritize the pipe replacement in water pressurized networks. The criterion of grouping the pipelines eligible for obtaining the economic prioritization scheme is a specific problem for utility managers and the more homogeneous the District Metering Area (DMA) is, the better results are expected.

With these limitations, an economic prioritization is proposed for minimizing the period of time required to recoup the funds invested (payback period). This study considers direct costs as the cost of purchasing and installing the pipe (e.g., excavation, repaving, etc.) and also as the cost of the water and energy savings (calculated using the energy audit; Cabrera et.al., 2010), indirect costs, environmental costs, social costs and opportunity costs (Rogers, 2002). Social costs are taxes proposed to compensate for the inconveniences created to people by public works and environmental costs are taxes destined to minimize the impact on the environment derived from the abstraction of water. Finally, the opportunity costs are the money savings derived from sharing some costs with other utilities (i.e. machinery, staff, tools, etc.).

The novelty of this methodology deals with the comparison between the current state of WDN (taking into account the rates of leakage obtained with the use of the water audit; IWA, 2000) and those obtained after the renewal of each of the *m* pipes which are part of the network (formulating the problem as a discrete optimization problem). The assessment of water and energy savings is based on hydraulic models to calculate the response of each pipe replacement, and the pipe with lowest payback periods should be the first selected for replacement. The lowest payback period is obtained for the pipe with the lowest ratio between investments and money savings. It is also pinpointed that pipelines with the largest water and energy savings are not necessarily the first selected for replacement according to this criterion.

The manuscript is organised as follows. Section 2.1 shows the simulation of leakage in WDN while section 2,2 shows the effect of every replacement with regard to water and energy consumption (described in Appendix A). The replacement criteria analysed in this paper are shown in section 2.3 and the definition of a real DMA where this method have been used in Section 2.4 (and also in Appendix B). The results obtained in the case study are shown in sections 3.1 and 3.2 and the effect of other costs apart from the direct costs are described in Section 3.3. The effect of performing a pressure driven analysis in comparison with a demand driven analysis is shown at Appendix C,a detailed step by step prioritization case is shown at Appendix D and a sensitivity analysis of the effect of the environmental, opportunity and social costs is depicted in Appendix E.

2. MATERIAL AND METHODS

A calibrated hydraulic simulation model is required to calculate water and energy audits of the pressurized water network.

2.1. Simulation of the leaky network

This approach deals with the idea of adding an emitter—a device that models the flow through a nozzle— at each node of the network (Cobacho et. al., 2015; Eq.1) in order to considers water leakage as pressure-dependent of node demands.

$$q_{li}(t) = C_{E,i} \cdot \left[\Delta H_i(t)\right]^{\alpha} = K_f \cdot \gamma_{pi} \cdot \left[\Delta H_i(t)\right]^{\alpha} \qquad (1)$$

Where $q_{li}(t)$ (m^3/s) is the sum of the background and bursts leakage flow rate at node i, $C_{E,i}$ ($m^{3-\alpha}/s$) is the emitter coefficient, $\Delta H_i(t)$ (m) is the pressure variation through the leak at time t; and α (-) is the pressure exponent that models the characteristics of the pipe material. K_f ($m^{3-\alpha}/s$) is the global value which considers the leakage level and γ_{pi} (-) is a weighted leakage factor which represents the importance of each node with regard to leakage. This equation produces good results if the pressure exponent ranges between 0.5-2.95 (Van Zyl and Malde,

2017) and if the pressure in the DMA is above the threshold pressure value (normal functioning with no pressure deficient conditions). In case of pressure deficit, pressure-driven simulation should be considered.

Since the location of background leakages is not known, it can be assumed that leakage is uniformly distributed along every pipeline of the WDN. Based on common modelling assumptions, water leakage at nodes is equal to the water losses produced in the half of all pipes connected to it. (Eq. 2). Let's assume that the leakage factor γ_{pi} can just be the pipe length.

$$\gamma_{pi} = \frac{\sum \gamma_j/2}{\gamma_T} = \frac{L_1/2 + L_2/2 + \dots + L_j/2}{L_T} \qquad (2)$$

Where $L_{j,}$ (m) are the lengths of pipes connected to each node and L_T (m) is the sum of all pipe lengths of the network. So there is a different factor for each node and must sum to one. If leakage in the DMA is not homogeneous, these γ_{pi} coefficients may adopt various values (such us the number of repairs per pipe length) with the restriction that the sum of the *n* coefficients must sum to one.

2.2. Simulation of the m-replacement Cases

Given a network with *m* pipelines eligible for replacement, *m* scenarios may arise for analysing water and energy consumption. The replacement of each pipeline assumes it as a leak free pipeline. It means that the burn-in phase at bathtub curve of the life cycle of a buried pipe (Kleiner and Rajani, 2001) is over and there is not any break after the replacement. As a consequence of the replacement, new weighted leakage factors (Eq. 2) are expected

For instance, if the jth pipe has been selected for replacement and the leakage factor γ_{pi} is now calculated as follows (Eq. 3):

$$\gamma_{pi} = \frac{\sum \gamma_j/2}{\gamma_T} = \frac{0 + L_{j+1}/2 + L_{j+2}/2}{L_T} \qquad (3)$$

Each one of the possible scenarios have new values in some of the *n* (number of nodes) weighted leakage factors. These new values involves changes in some of the *n* emitters (there is not any change at the K_f value; Eq. 1) and new levels of water leakage. Moreover, pipe roughness is a property that may change as pipes age and this variation can have a large effect on the WDN headlosses . In order to arrange this effect, pipe roughness of the new pipe have lower values than the aged pipe. The changes performed in leakage parameters (at nodal level) and in the pipe roughness (at pipe level) involves a different flow distribution through the system and consequently, new pressure levels at every node of the network. Moreover, the calculation of leakage in the new *m* scenarios (using water and energy audits as described in Appendix A and comparing the new results with the 0-case scenario) reveals the joint effect of these new parameters and of the hydraulic status.

2.3. Pipe renewal criteria

2.3.1. Unit headloss prioritization criterion

The unit headloss represents the energy headlosses per length of the pipe, quantified in meters of water column dissipated by friction per kilometre of pipeline (m /Km). It depends on flow and on the hydraulic resistance of the pipe. Pipe hydraulic resistance in WDNs is computed for fully turbulent conditions (transitional and laminar flow are only in theory) due to the presence of connections, changes in pipe directions and variation of water demands. So, this method consists on selecting the pipe with highest daily average unit headloss among the *m* potential candidates as the first pipeline to be replaced. The key advantage of this criteria is the simplicity and it is a commonly adopted approach by water utilities which plan rehabilitation mainly based on pipe age (which are assumed to have higher internal roughness), but, in contrast, it does not consider the impact of a single-pipe replacement on the hydraulic behaviour of the whole network.

2.3.2. Economic prioritization criterion

The economic prioritization criterion involves calculating the water and energy audits for each of the *m* cases and comparing with the zero case (current state of the network). The indicator that should be used for obtaining the prioritization scheme is the payback period.

Moreover, this investment has to be paid at present time while water and energy savings are periodically obtained. In order to be able to compare, all costs should be expressed in monetary units at present time with the use of the equivalent continuous discount rate, *r*.

The operation costs that the utility should face in a non-replacement scenario ("the laissez faire" option or the cost of doing nothing) from the present time —t_p— to the time t can be expressed as (Eq. 4):

$$C_{tp}^{tot}(t) = \int_{tp}^{t} \left(C_F + C_M + (C_W + C_{ENV})V_{inj} + C_{WE}\, E_{input}\right). e^{-rt} dt = \int_{tp}^{t} B_i\, e^{-rt} dt \qquad (4)$$

where C_F (EUR) is the fixed costs with regard to operation and maintenance of the network, C_M (EUR) is the average break repair cost (a value that can be calculated as the repair cost of a single break multiplied by the number of breaks that appear from present time to time t), C_W (EUR/m^3) is the cost of water (this value is a sum of the fixed cost depending on the utility structure and the variable costs of collection, treatment and distribution, excluding energy costs), C_{ENV} (EUR/m^3) is the environmental cost of water, highly variable, from 0.84 to 0 €/m^3 in Denmark and Spain respectively (EPO, 2010) and C_{WE} (EUR/kWh) is the cost of the energy consumed, sum of the variable costs of energy in the collection, treatment and distribution stages of the urban water cycle. Finally, B_i (EUR) is the operation costs of the water network for the period (tp-t).

Analogous to the previous equation, the present value of the operation costs that the utility should face from now (replacement of the i^{th} pipe) to "t" is calculated as (Eq. 5):

$$C_{tp\,i}^{tot}(t) = \left(\left(C_{p-i} + C_{inst-i} \right) + C_{ind-i} - C_{Oi} + C_{Si} \right) - \int_{tp}^{t} \left(C_F + C_M + (C_W + C_{ENV}) V_{inj}^{*} + \right.$$

$$\left. + C_{WE}\, E_{input}^{*} \right). e^{-rt} dt = I_i - \int_{tp}^{t} B_i^{*}. e^{-rt} dt \qquad (5)$$

Where C_{p-i} (EUR) is the pipe cost itself, $C_{inst-i\ 1}$ (EUR) is the pipe installation costs (these both grouped represent the direct pipe replacement costs). The indirect costs (C_{ind-i}; EUR) of pipe replacement are administration, personnel, security costs, etc. Social costs (C_{Si}; EUR) are proposed to compensate for the inconveniences created to people by public works. The opportunity costs (C_{Oi} ; EUR) are associated to the savings derived from renewing the pipe while performing other utility or road works which are more urgent and as a consequence, some costs are shared (i.e. machinery, staff, tools, etc.) and the savings can even reach the total cost of the installation if other works are in charge of digging and replacing the pavement. I_i (EUR) represents the investment performed in pipe *i* and B_i^* (EUR) is the new operation cost encompassing the energy and water consumed after the replacement of the *i*-pipe.

Finally, the equation resulting when comparing the operation costs if the *laissez faire* option with the replacement of pipe *i* results in equations is (Eq. 6):

$$C_{tp\,i}^{tot}(t) - C_{tp}^{tot}(t) = I_i + \int_{tp}^{t} (B_i^{*} - B_i). e^{-rt} dt = I_i - \int_{tp}^{t} S_i. e^{-rt} dt \qquad (6)$$

where S_i (EUR) are the economic savings obtained by the renovation (B_i^* has a lower value than B_i, as the replacement involves water and energy savings). Note that the fixed costs (C_F; EUR) are equal for each of the cases compared and the maintenance cost are considered to have similar values in homogeneous DMAs and due to this, irrelevant for this study. Equating to zero the derivative of Eq. (6), the payback period of the investment (Eq. 7) is calculated:

$$T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) \quad (7)$$

Where T_i (months) is the payback period which is the value to minimize as lower values involve higher water and energy savings per monetary unit invested.

2.4. Numerical example

To illustrate the proposed methodology, a numerical example is presented. Figure 1 shows a DMA in a western Mediterranean city of Spain. The pipe material is ductile iron and the pipe roughness for the aged pipes are 0.2 mm, these figures are of the same order of magnitude as those considered by Christensen (2009) and the pipe roughness of the new installed pipe is equal to 0.1mm (McGovern, 2011), a usual value in WDN. The emitter exponent is equal to 1. The utility facilitates the leakage rate of the network (10%) and the minimum service pressure required is 20 m.w.c.

The cost of water and energy is 1,89 EUR/m^3 (INE, 2016) and 0,084 EUR/kWh (MINETAD, 2017) respectively. The renewal cost of pipes considered in the study is 1,096 EUR/m/mm $(C_{p-i}+C_{inst-i})$; a real value obtained by a water utility which operates in Spain (this cost allow the practitioners to get the cost of every pipeline in the water network as the cost is proportioned considering the pipe length in m and the pipe diameter in mm).

The indirect cost will be considered as a 6% of the direct costs (a value proportioned by the water utility). The social, the opportunity and the environmental costs are zero for the DMA analysed (although an analysis of the specific importance of each of them are calculated later). Finally, the equivalent continuous discount rate is r=2%.

As this methodology is very time-consuming (the values of energy savings at every time step periods vary, daily sums of energy/water saved have been calculated), every hydraulic simulation of the 617 scenarios (with their water and energy audits) have been calculated using the Matlab® code to assist with the EPAnet toolkit (Rossman, 2000).

3. RESULTS AND DISCUSSION

3.1. Prioritization results in the unit headlosses methodology

Results are depicted in Table 1 where the 4 pipes with the highest average values of the unit headlosses are displayed. According to these, the renovation order is pipe 105, 403, 613 and 615. This methodology does not consider the global energy and water savings produced as a consequence of a pipe renewal so there is no additional information about the impact of the renewal action.

3.2. Economic criteria prioritization results

The priority obtained is different compared to the unit headlosses methodology. The results indicate that the new order is now pipe 8, 403, 615 and 77 (Table 1).

If the unit headloss methodology is the criterion selected for replacement, pipe 105 (Best result) involves a daily savings of 157,10 liters and 0,024kWh, while pipe 8 replacement would save (136,14 l/day and 0,021 kWh/day). But the investment performed with Pipe 105 replacement is equal to 1068,54 € (as the length of the pipe is 18,2m and its current diameter is 50,53 mm) while the investment of Pipe 8 replacement is equal to 767,67 € (length 16,57m , diameter 39,87mm) and considering this numbers, pipe 8 replacement produces higher savings (1 EUR saves 64,78 litres and 0,01 kwh per year) than pipe 105 replacement (in which 1 EUR saves 53,75 litres and 0,008 kWh).

Table 1 collects the payback period (in months). As it can be concluded from those results, when high hydraulic efficiency scenarios are analysed, economic investment are slowly recovered because the energy and water savings are low (as in the current case study); on the opposite, when water networks present low levels of water losses, pipe replacement planning are very much interesting from an economic point of view. Some pipe replacements considered in the calculations shows payback periods equal to infinity (55 pipelines out of 617), in other words, the investment is never recouped as the low savings produced.

3.3. Influence of the Environmental, Social and Opportunity costs

In order to consider the influence of the environmental cost on the payback period of the investment, some values (€/m^3) are proposed (0,05; 0,1; 0,15; 0,2). This figures are low compared with the aforementioned values of Denmark (EPO, 2010). The effect of the environmental costs bears little surprise, and the higher environmental costs results in the lowest payback period (Table 2).

The social costs values considered should be different with regard to every street in the DMA studied. Here, streets N1, N2, N3 and N4 (Figure 1; 109 pipes whose length is 2224 m, 20,97% of the total network) are considered to have social cost equal to 0,109; 0,219 and 0.329 €/m/mm (10, 20 and 30% of 1,096 €/m/mm, sum of the pipe and installation costs; Cobacho et. al., 2009) while the rest of the network have social costs equal to 0 €/m/mm. These costs influence the payback periods increasing the payback period for the pipelines located in these streets. The prioritization scheme showed in Table 1 is not modified as the pipelines selected for replacement are not installed in these streets.

Finally, the Opportunity Costs considered can be a reduction of 10%, 20% and up to 30% of the pipe replacement cost (Cobacho et. al., 2009) — in other words, a reduction of the pipe cost of 0,109, 0,219 and 0,329 €/m/mm for every pipeline considered—. The results indicate that the payback period of the ith pipe replacement decreases if the opportunity arises. As it may be observed at Table 2, the payback period for pipe 8 is equal to 107,90 months and if opportunity costs are larger than 0.0695 (pipe 403) and 0.1446 €/mm/m (pipe 615), the payback period is lower than this value (107.90) and opportunity must be seized. The calculation of the threshold value (0,0695 €/mm/m) for pipe 403 is described in detail in Appendix E.

4. CONCLUSIONS

Water utility managers have considered the unit headloss methodology as one of the criterion for pipe replacement. However, this study demonstrates that following this criterion neither water and energy nor the financial investment is optimized and significant savings are not fully exploited.

The methodology proposed to prioritize the replacement plan is based on economic factors and involves maximising the energy and water savings per monetary unit invested. In each of the m scenarios considered, the diameter of the aged pipe has been maintained and a new roughness value has been considered to model its hydraulic response. Energy and water audits are carried out in leaky networks to calculate the savings obtained as a consequence of the replacement.

Results have demonstrated that opportunity costs do not necessarily involve large savings and not always the prioritization scheme is modified. It has been proved that a threshold value for taking or rejecting the opportunity exists and it can be calculated now. On the other hand, the existence of environmental costs of water involve lower payback periods, and social costs are considered to make the simulation more realistic, as in every DMA, water managers cannot decide when to carry out the take the digging and repaving works without considering the social problems.

Although leakage reduction is the main positive effect of pipe replacement, it implicitly reduce the risk of bursts and service interruption (considered in the social cost) and it also increases the hydraulic capacity of the WDN. Scenarios with low hydraulic efficiency (high leakage flowrate) involve quickly recovery of the economic investment because of the high energy and water savings.

This methodology should be used for homogenous groups of pipelines (all of them with the same age). The more homogeneous the DMA is; the better results are obtained. In other words, it cannot be used for comparing pipelines at different ages. Finally, as pipelines in the DMA are considered to have the same age, the number of breaks and their repair costs (maintenance costs) can be considered as fixed costs, and they can also be irrelevant for this study.

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Figure 1. General layout of the network

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Table 1. Prioritization results for the unit headloss criterion (a) and the economic criterion (b).

Table 2. Effect of the environmental and opportunity costs in the payback period (in Months)

9. NOTATION

B_i (EUR) Operation Cost before pipe replacement

B_i^* (EUR) Operation Cost after i-pipe replacement

$C_{E,i}$ ($m^{3-\alpha}/s$) Emitter coefficient at node i.

C_{ENV}(EUR/m^3) Environmental cost of water

C_F (EUR) Fixed costs of operation and maintenance

C_M (EUR) Average break repair cost

$C_{tp}^{tot}(t)$ (EUR) Present value of the total cost in the zero-action performed

$C_{tp\,i}^{tot}(t)$ (EUR) Present value of the total cost in the decision of renovation of pipe i

C_W (EUR/m^3) Cost of water

C_{WE} (EUR/kWh) Cost of the energy

C_{p-i} (EUR) Pipe costs

C_{inst-i} (EUR) Installation Costs

C_{ind} (EUR) Indirect Costs

C_{si} (EUR) Social Costs

C_{Oi} (EUR) Opportunity Costs

J (m/km) Unit headloss of a pipe

I_i (EUR) Investment performed

L_{pi} (m) Weighted length of the node i

L_{pi+1} (EUR) Weighted length of the pipe i+1

${L_{pi}}^*$ (m) Weighted length of the node i after the renovation of a pipe

${L_{pi+1}}^*$ (m) Weighted length of the node i+1 after the renovation of a pipe

L_T (m) Total length of the network

K_f ($m^{3-\alpha}/s$) Global value of the emitters.

$\Delta H_i(t)$ (m) Pressure variation through the leak at node i

n (-) Number of demand nodes of the network

m (-) Number of pipes of the network

P_{i-ser} (m.c.w.) minimum service pressure required for supplied demand

$q_{li}(t)$ (m^3/s) Leakage flow rate at node i at time t

S_i (EUR) Economic savings obtained by the reduction of the leaks after renovation of pipe i

T_i (months) Payback Period

$V_{inj}(t)$ (m^3/s) Total volume injected for the simulation period

α (-) Emitter exponent

γ (N/m^3) Specific weight of water

γ_{pi} (-) Weighted leakage factor

$\Delta H_i(t)$ (m.w.c.) Pressure variation through the leak

Table 1. Prioritization results for the unit headloss criterion (a) and the economic criterion (b).

(a) Unit Headlosses prioritization				(b) Economic prioritization			
	ID	**A***	**B***		**ID**	**A***	**B***
1st	*105*	*0,806*	*132,79*	*1st*	*8*	*0,094*	*107,90*
2nd	403	*0,574*	*115,99*	*2nd*	*403*	*0,574*	*115,99*
3rd	613	*0,570*	*132,41*	*3rd*	*615*	*0,549*	*126,21*
4th	615	*0,549*	*126,21*	*4th*	77	*0,038*	*127,05*

*: A (m/km); B, (months)

Table 2. Payback period (in months) for replacement without considering additional costs

	ID	**Pipe costs (€/m)**	**Volume savings (m^3/day)**	**Energy savings (kWh/day)**	**I_i (€)**	**S_i (€)**	**Payback period (months)**
1st	8	43.70	0.14	0.02	767.51	7.77	107.88
2nd	403	46.97	0.12	0.0	705.90	6.70	115.94
3rd	615	52.45	0.30	0.0	1,927.87	16.95	126.11
-	229	209.03	0.70	0.1	17,490.80	39.64	797.86

Table 3. Effect of the environmental costs on the payback period (in months)

Env. Costs (€/m^3)			0.05	0.1	0.15	0.2	0.05	0.1	0.15	0.2
	ID	**I_i (€)**	**S_i (€)**				**Payback period (months)**			
1st	8	767.51	7.977	8.182	8.39	8.59	104.86	102.01	99.31	96.74
2nd	403	705.90	6.871	7.047	7.22	7.40	112.68	109.59	106.67	103.90
3rd	615	1,927.87	17.395	17.840	18.29	18.73	122.53	119.15	115.95	112.91
-	229	17,490.80	40.678	41.720	42.76	43.80	756.61	719.88	686.91	657.11

Table 4. Effect of the opportunity costs on the payback period (in months)

Opp. Costs (€/m/mm)			0.1096	0.2192	0.3288	0.1096	0.2192	0.3288
	ID	S_i **(€)**	I_i **(€)**			**Payback period (months)**		
1st	8	7.773	690.76	614.01	537.26	96.18	84.70	73.43
2nd	403	6.696	635.31	564.72	494.13	103.29	90.89	78.75
3rd	615	16.949	1,735.08	1,542.29	1,349.51	112.24	98.68	85.42
-	229	39.637	15,741.72	13,992.64	12,243.56	650.68	532.58	433.95

Table 5. Effect of the social costs on the payback period (in months)

S. costs (€/m/mm)			0.1096	0.2192	0.3288	0.1096	0.2192	0.3288
	ID	S_i **(€)**	I_i **(€)**			**Payback period (months)**		
1st	8	7.773	767.51			107.88		
2nd	403	6.696	705.90			115.94		
3rd	615	16.949	1,927.87			126.11		
-	229	39.637	19,239.88	20,985.77	22,738.05	993.31	1,284.38	1,875.50

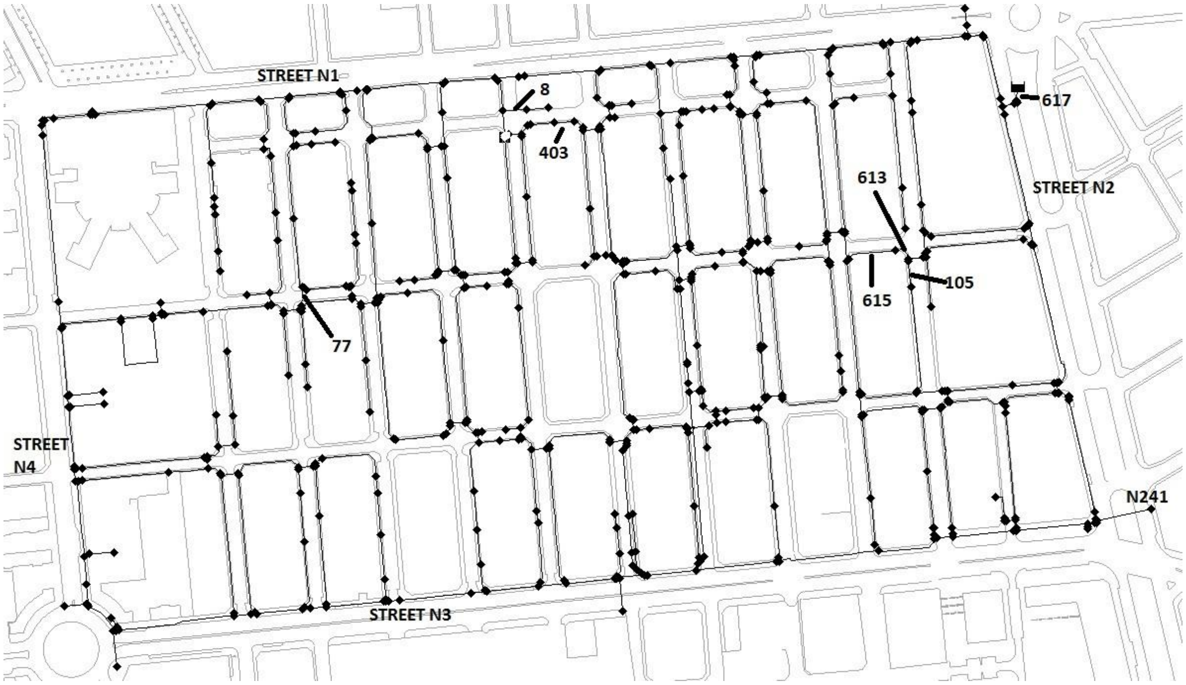


Figure 1. Layout of the network

Appendix A. Water and Energy Audits

Once the leakage can be adequately simulated by the hydraulic software, both the water and energy audit (Cabrera *et. al.* 2010) can be performed (Equations A1 and A2):

$$V_{inj}(t) = V_R(t) + V_L(t) \tag{A1}$$

where $V_{inj}(t)$ is the volume injected into the network, $V_R(t)$ is the volume delivered to users and $V_L(t)$ is the volume lost through leaks;

$$E_{input}(t) = E_N(t) + E_P(t) = E_U(t) + E_L(t) + E_F(t) + \Delta E_C(t) \tag{A2}$$

where $E_N(t)$ is the energy supplied by reservoirs, $E_P(t)$ is the energy supplied by pumps, $E_{input}(t)$ is the energy consumption of the network (sum of the two previous), $E_U(t)$ is the energy delivered to the users (throughout the water supplied), $E_L(t)$ is the energy lost through water losses, $E_F(t)$ is the energy dissipated in friction at pipes and $\Delta E_C(t)$ is the energy that can be stored in a compensation tank which accumulates water during low consumption hours while releasing it in peak hours.

References

Cabrera, E., Pardo, M. A., Cobacho, R. & Cabrera, E., Jr. 2010 Energy audit of water networks. *Journal of Water Resources Planning and Management* **136** (6), 669–677.

Appendix B. Full Information about the Network of the Case Study

The DMA considered here supplies water to 10,000 inhabitants and consists of 561 nodes and 617 pipes. The total length of the network is 10.61 km. The values of the coefficients (each value is valid for half an hour), which consider water consumption at different hours of the day, are depicted in Table B1.

Table B1. Hourly coefficients of water demand modulation for pattern 1

T	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**
C	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
T	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**	**10**	**10.5**	**11**	**11.5**
C	0.13	0.13	0.22	0.35	0.48	0.48	0.57	0.71	0.65	0.68	0.64	0.68
T	**12**	**12.5**	**13**	**13.5**	**14**	**14.5**	**15**	**15.5**	**16**	**16.5**	**17**	**17.5**
C	0.58	0.59	0.54	0.51	0.46	0.60	0.56	0.64	0.47	0.41	0.37	0.40
T	**18**	**18.5**	**19**	**19.5**	**20**	**20.5**	**21**	**21.5**	**22**	**22.5**	**23**	**23.5**
C	0.39	0.35	0.26	0.32	0.32	0.28	0.33	0.30	0.35	0.27	0.21	0.17

Water and Energy results in the Case Study

The results obtained when performing water and energy audits are shown in Table B2. Moreover, the global value which considers the background leakage (K_f ; m$^{2-\alpha}$ s^{-1}) is also shown here.

Table B2. Results of the water and energy audit for the simulation period (2 days)

	Water audit		Energy audit	
0 Case	**Injected water (m³)**	1,808.42	E_N	282.94
	Delivered water (m³)	1,628.22	E_U (kWh)	253.90 (89.73%)
	Real losses (m³)	180.20	E_L (kWh)	28.11 (9.93%)
	Error (%)	0.01%	E_F (kWh)	0.94 (0.33%)
	K_{global}	0.16	**Error (%)**	0.00%
Pipe 8 replacement	**Water audit**		**Energy audit**	
	Injected water (m³)	1,808.15	E_N (kWh)	282.90 (100%)
	Delivered water (m³)	1,628.22	E_U (kWh)	253.90 (89.74%)
	Real losses (m³)	179.93	E_L (kWh)	28.06 (9.91%)
	Error (%)	0.01%	E_F (kWh)	0.94 (0.33%)
			Error (%)	0.00%

Appendix C. Pressure Driven Analysis vs Demand Driven Analysis

The demand driven simulation approach developed here can be considered appropriate when the system operates with pressures higher than the minimum service pressure required for supplied demand – $P_{i\text{-}ser}$ – (Guistolisi *et. al.* 2008). This means that if the pressure in the DMA is lower than this threshold pressure value ($P_{i\text{-}ser}$), a pressure driven demand analysis (PDA) is required.

The numerical example is calculated using EPAnet2.0 (Demand Driven Analysis; Rossman 2000) and using WDNetXL, an integrated system for WDN analysis (Pressure Driven Analysis; Giustolisi *et al.* 2011). In both models, leakages have been modelled as emitters added to every node in the network. The comparison of the results is depicted in Figure C1 —flowrates at pipe 617 — and at Figure C2 — pressure at node 241. Link 617 has been selected for this as it is the pipe connecting this DMA with others and thus, all the injected flow is supplied though this pipeline, whereas node 241 has been selected for this comparison as it is the node with the highest water consumption. It may be observed that the pressure in node 241 and flow at link 617 have the same values using PDA and DDA hydraulic software. The quotient of the two values shown when comparing pressure has an average value of 0.999 and a standard deviation of 0.005 (which means that every single value is the same) and when comparing flow an average value of 0.954 and a standard deviation of 0.124. Moreover, the water balance in both scenarios is the same as the injected flow in the EPAnet case, equal to 892.98 m^3/day, while in the WDNetXL case it is equal to 886.68 m^3/day.

The pressure at the DMA analysed is always above the minimum service pressure required for the supplied demand ($P_{i\text{-}ser}$, Figure C2), and this situation indicates that the network is oversized and the emulation of leakages as outflows from emitters is appropriate (as also the use of a demand-driven analysis).

Figure C1. Daily flowrates at pipe 617 for the EPAnet (Demand Driven Analysis, DDA) and WDNetXL (Pressure Driven Analysis, PDA) approaches.

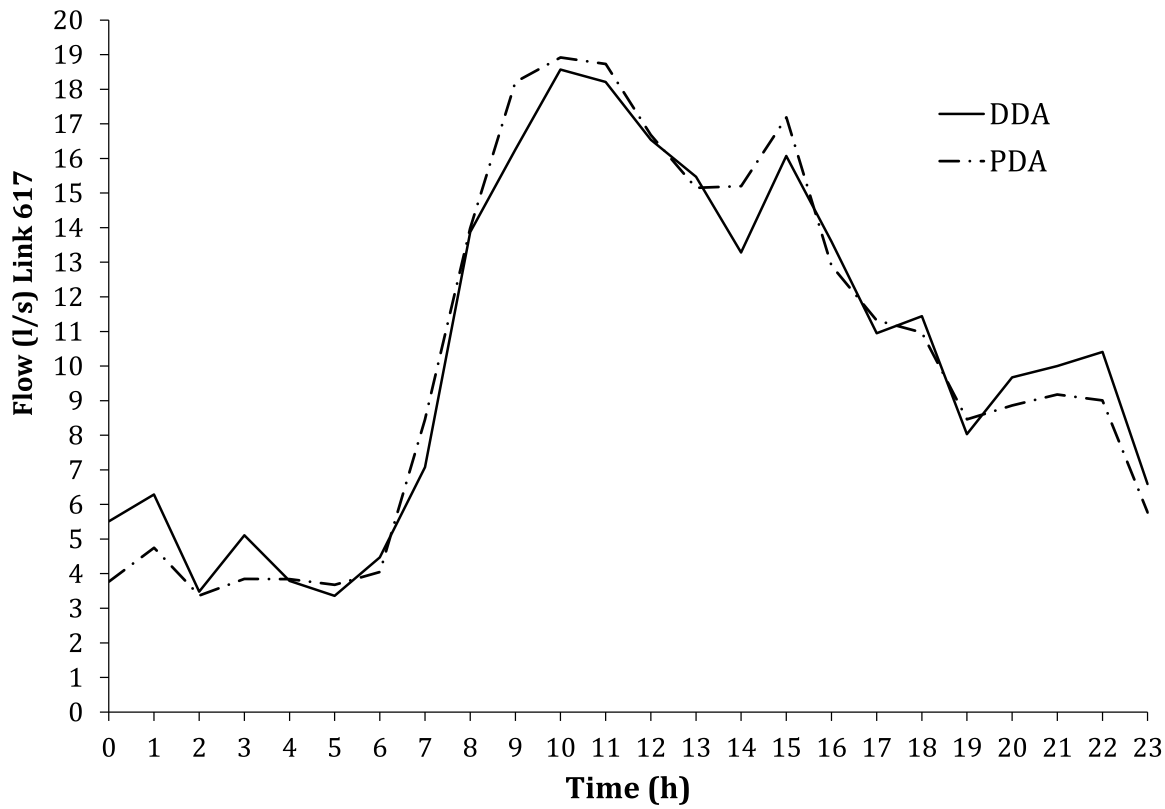
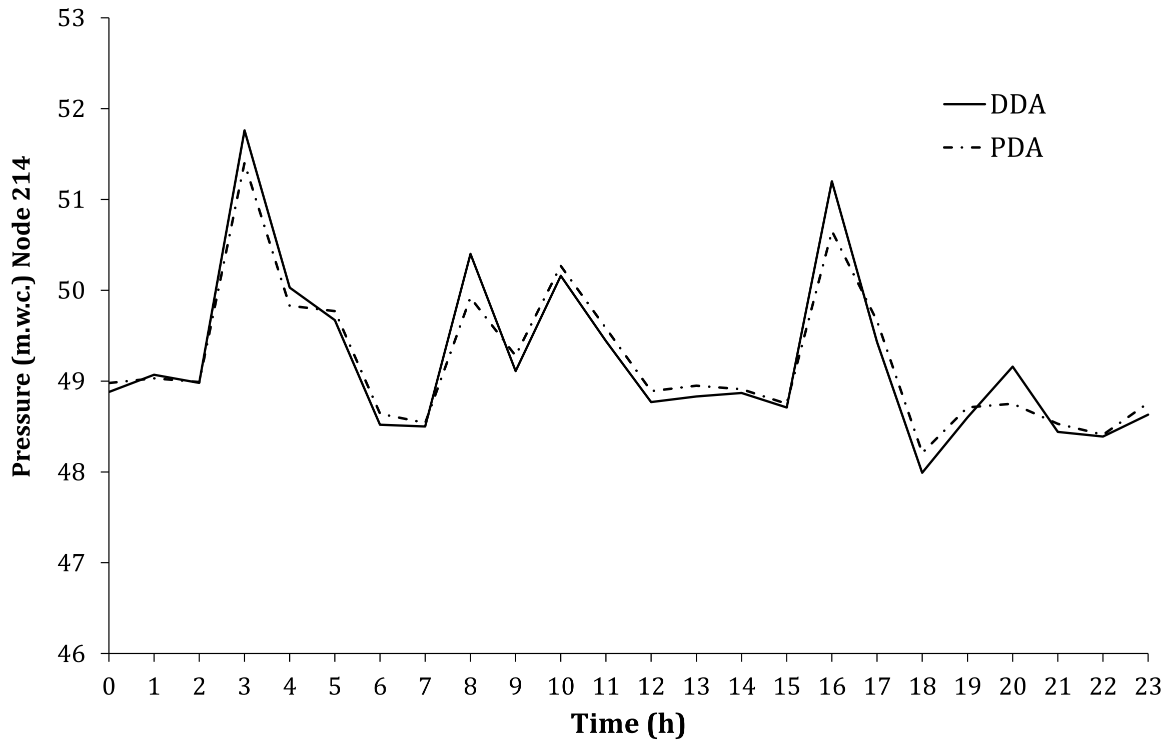


Figure C2. Daily Pressure at node 241 for the EPAnet (Demand Driven Analysis; DDA) and WDNetXL (Pressure Driven Analysis, PDA) approaches. Physical characteristics and normal operation values for pipe variables.



References

Guistolisi, O., Savic, D. & Kapelan, Z. 2008 Pressure-driven demand and leakage simulation for water distribution networks. *Journal of Hydraulic Engineering* **134** (5), 626–635.

Giustolisi, O., Savic, D. A., Berardi, L. & Laucelli, D. 2011 An Excel-based solution to bring water distribution network analysis closer to users. In: *Proceedings of Computing and Control for the Water Industry (CCWI), September 5–7, Exeter*, *UK*, Vol. 3 (D. A. Savic, Z. Kapelan & D. Butler, eds), pp. 805–810.

Rossman, L. A. 2000 *EPANET 2: User's Manual*. US Environmental Protection Agency, Cincinnati, OH, USA.

Appendix D. Example of Calculation of the Economic Prioritization for One Pipe

The payback period for pipe 8 (Ø = 39.87mm and L = 16.57m) is calculated as follows:

- Investment $= I_{ij} = \left((C_{11i}+C_{12i}) + C_{ind-i} - C_{Oi} + C_{Si}\right) =$

  = (1.096*39.87*16.57) * 1.06-0+0 = 767.67 €

- Daily water savings = (1808.36-1808.09)/2 = 0.136 m^3/day (Table B2)

- Daily energy savings = (282.93-282.89)/2 = 0.021 kWh/day (Table B2)

- Cost of the water losses = 1.89 €/m^3 *0.136 m^3/day = 0.257 €/day

- Cost of the energy losses = 0.084 €/kWh*0.021 kWh/day = 0.002 €/day

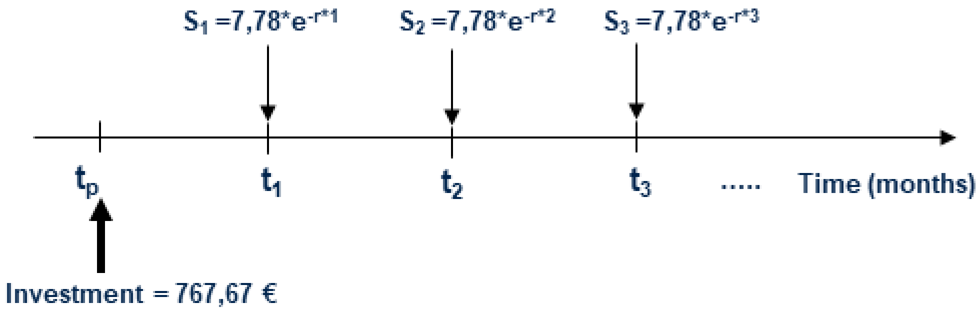
- Money savings = 0.257+0.002 = 0.259 €/day = 7.78 €/month (1 month = 30 days)

- r = 2% annually, r = 0.17% monthly

-Payback period, $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) = \frac{-1}{0.0017} . \ln(1 - \frac{767.67*0.0017}{7.78})$ = 107.90 months.

This payback period considers the depreciation of money with the equivalent continuous discount rate, r. The timescale for the investment and savings are shown in Figure D1, where t_p is the present time (when the pipe replacement has just been performed) and S_i represents the economic savings originated after the i^{th} month

Figure D1. Timescale considered for savings and investment performed for pipe 8 replacement.



Appendix E. Example of the Calculation of the Economic Prioritization Considering Environmental, Opportunity and Social costs. Sensitivity Analysis.

The payback period for pipe 229 (Ø = 190.72 mm and L = 78.94m) is calculated as follows:

- Investment $= I_{ij} = \left((C_{11i}+C_{12i}) + C_{ind-i} - C_{Oi} + C_{Si}\right) =$

= (1.096*78.94*190.72) * 1.06-0+0 = 17,490.80 €

- Daily water savings = 0.694 m^3/day
- Daily energy savings = 0.1085 kWh/day
- Cost of the water losses = 1.89 €/m^3 *0.694 m^3/day =1.31 €/day
- Cost of the energy losses = 0.084 €/kWh*0.1085 kWh/day = 0.009 €/day
- Money savings = (1.31+0.009)*30 = 39.64 €/month (1 month = 30 days)
- r = 2% annually, r = 0.17% monthly

-Payback period, $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) = \frac{-1}{0.0017} . \ln(1 - \frac{17{,}490.8 * 0.0017}{39.64})$ = 797.86 months.

E1. Effect of the environmental costs

If the environmental cost equal to 0.15 €/m³ is considered (or in other words, the cost of water is increased because of an environmental tax), the new payback period is:

- Investment $= I_{ij}$ =17,490.80 € (not dependent on environmental costs)
- Cost of the water losses = (1.89 +0.15) €/m³ *0.694 m³/day =1.41 €/day
- Cost of the energy losses = 0.084 €/kWh*0.1085 kWh/day = 0.009 €/day
- Money savings = (1.41+0.009)*30 = 42.76 €/month
- r = 2% annual, r = 0.17% monthly

-Payback period, $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) = \frac{-1}{0.0017} . \ln(1 - \frac{17{,}490.8 * 0.0017}{42.76}) = 686.91$ months.

With these data, the effect of the environmental cost of water can be observed in Figures E1 and E2. The higher the environmental cost of water, the lower the payback period that is obtained. Moreover, in Figure E1, it can be observed that if authorities consider these environmental costs, the payback period of replacement is reduced because of the increase of the cost of water losses. In short, these taxes involve higher concern with regard to reducing leakage rates.

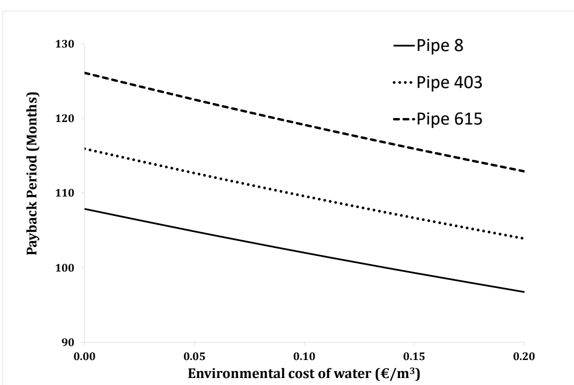


Figure E1. Effect of the environmental costs of water in the payback period of the investment for the pipes selected with the economic prioritization criterion.

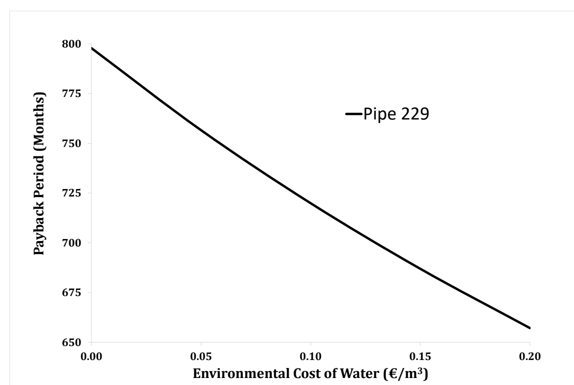


Figure E2. Effect of the environmental costs of water in the payback period (pipe 229).

E2. Effect of the opportunity costs

Opportunity costs are associated with the savings derived from replacing the pipe while performing other utility or road works which are more urgent. If these savings are quantified as equal to 0.2192 €/m/mm, the new payback period is:

- Investment $= I_{ij} = \left((C_{11i}+C_{12i}) + C_{ind-i} - C_{Oi} + C_{Si}\right) =$

$= ((1.096*78.94*190.72) * 1.06- (0.2192)*78.94*90.72*1.06+0 =$

$= 13{,}992.64$ €

- Money savings = 39.64 €/month (the same value as obtained before; it does not depend on the opportunity costs)

- Payback period, $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) = \frac{-1}{0.0017} . \ln(1 - \frac{13{,}992.64*0.0017}{39.64}) = 532.58$ months.

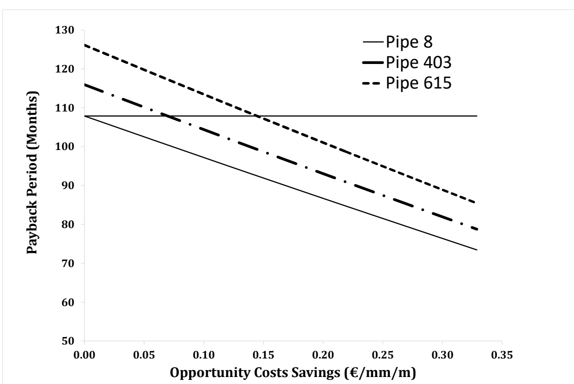


Figure E3. Effect of the opportunity costs on the payback period.

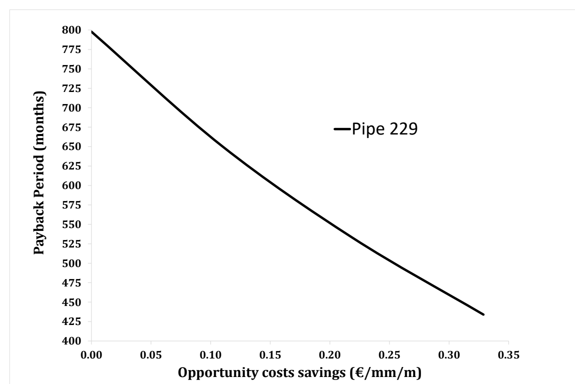


Figure E4. Effect of the opportunity costs on the payback period (pipe 229).

The effect of the Opportunity Costs is shown in Figures E3 and E4, and the higher the opportunity costs, the lower the payback period of the replacement. However, the prioritization scheme is only modified for pipe 403 and pipe 615 if opportunity costs are equal to or higher than 0.0695 and 0.1446 €/mm/m respectively (Figure E3).

To sum up, if opportunity costs are larger than 0.0695 €/mm/m, the payback period for pipe 403 is lower than 107.88 (payback period for pipe 8) and this opportunity should be taken. If opportunity costs are lower than this threshold value, the opportunity of sharing costs should not be considered.

This threshold value (0.0695 €/mm/m) can be obtained for pipe 403 (Ø = 42.85 mm and *L* = 14.18m) as follows:

The equation $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right)$ becomes the equation: $I_i = \frac{S_i\left(1-e^{-rT_i}\right)}{r}$ and the data are:

- Daily water savings = 0.117 m^3/day
- Daily energy savings = 0.0183 kWh/day
- Cost of the water losses = 1.89 €/m^3 *0.177 m^3/day =0.22 €/day
- Cost of the energy losses = 0.084 €/kWh*0.0183 kWh/day = 0.0015 €/day
- Money savings = (0.22+0.0015)*30 = 6.70 €/month
- *r* = 2% annually, *r* = 0.17% monthly

And the investment performed should be:

$$I_i = \frac{S_i\left(1-e^{-rT_i}\right)}{r} = \frac{6.7\left(1-e^{-0.0017*107.88}\right)}{0.0017} = 661.10\ €$$

And these investments are obtained with the following opportunity costs:

$$I_{ij} = \left((C_{11i}+C_{12i}) + C_{ind-i} - C_{Oi} + C_{Si}\right)$$

$$661.10 =((1.096*14.18*42.85) * 1.06- (C_{Oi})*14.18*42.85*1.06+0$$

obtaining the aforementioned result, $C_{Oi} = 0.0695$ €/mm/m.

E3. Effect of the social costs

Finally, social cost (economic compensation for the problems created by public works in the network) are in this case study only considered in streets N1, N2, N3 and N4. As pipeline 229 is in street N2, its potential replacement is affected by social costs equal to 0.2192 €/m/mm. The new payback period is:

- Investment $= I_{ij} = \left((C_{11i}+C_{12i}) + C_{ind-i} - C_{Oi} + C_{Si}\right) =$

  = ((1.096*78.94*190.72) * 1.06- 0+

  + (0.2192)*78.94*90.72*1.06 = 20,985.77€

- Money savings = 39.64 €/month (the same value as before)

-Payback period, $T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) = \frac{-1}{0.0017} . \ln(1 - \frac{20{,}985.77 * 0.0017}{39.64}) = 1{,}284.38$ months.

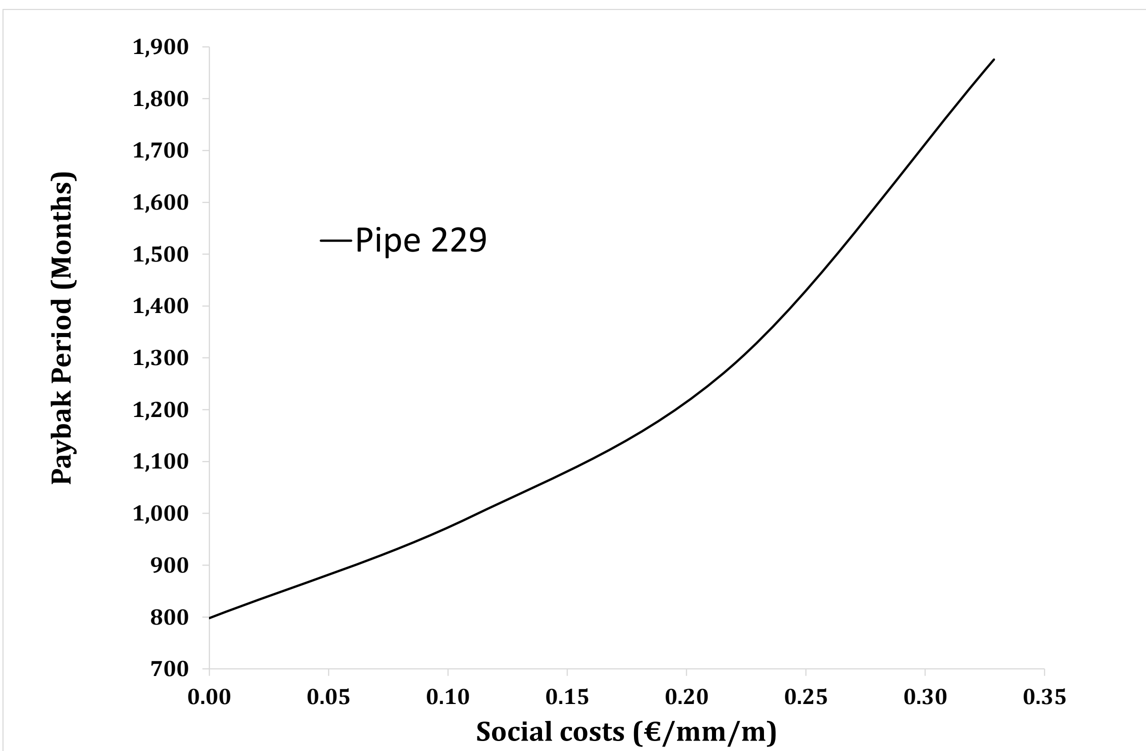


Figure E5. Effect of Social cost in the payback period for pipe 229.

The effect of the social costs is shown in Figure E5, and the higher taxes that the water utility has to pay in order to compensate for the problems originated involve larger payback periods. Finally, this graph has not been calculated for pipes 8, 403 and 615 due to these pipelines not being located in the streets where social costs are applied (N1, N2, N3 and N4).